

Models of SUSY Dark Matter

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- ★ mSUGRA model
- ★ Normal scalar mass hierarchy
- ★ NUHM1
- ★ NUHM2
- ★ MWDM
- ★ BWCA
- ★ LM3DM (compressed SUSY)
- ★ mixed moduli-AMSB (KKLT)



Some successes of SUSY GUT theories

- ★ quadratic divergence cancellation allows widely disparate scales to co-exist:
e.g. GUT scale $Q = 10^{16}$ GeV and weak scale $Q = 100$ GeV
- ★ gauge coupling unification!
- ★ Lightest Higgs mass $m_h \lesssim 130$ GeV as indicated by radiative corrections!
- ★ radiative breaking of EW symmetry if $m_t \sim 100 - 200$ GeV!
- ★ dark matter candidate: lightest neutralino \tilde{Z}_1
- ★ stable see-saw mechanism for neutrino mass
- ★ $SO(10)$ SUSY GUT: baryogenesis via leptogenesis

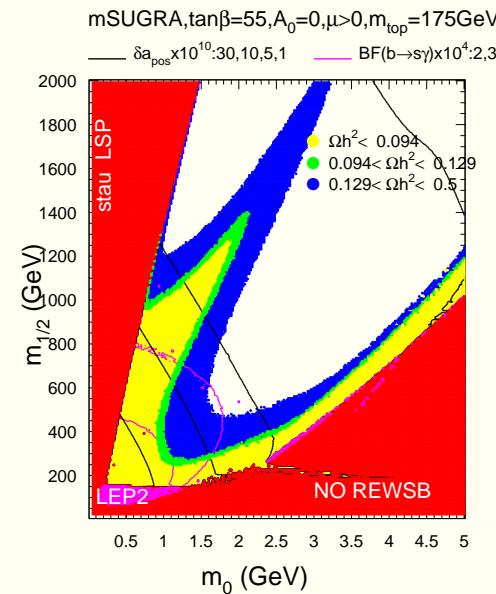
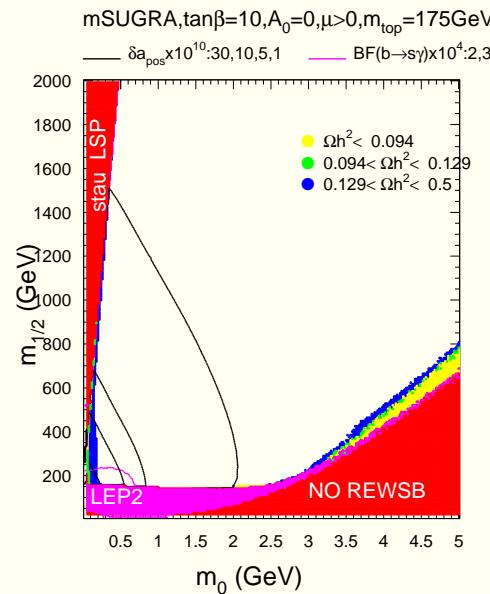
Our strategy:

- ★ Assume MSSM is valid effective theory between M_{weak} and M_{GUT}
 - LSP is stable: good candidate for CDM
- ★ Stipulate SSB terms at $Q = M_{GUT}$ and evaluate SSB at M_{weak} via RG evolution
 - EW symmetry broken radiatively by large m_t
- ★ Invoke
 - minimal flavor violation
 - ignore CP -viol. phases
- ★ Spectra generated with Isajet/Isasugra (Paige, Protop., HB, Tata)
- ★ We will use the measured value $\Omega_{CDM} h^2 = 0.105 \pm 0.01$ as a guide to allowed phenomenology! (Isatools: IsaReD)

Case 1: mSUGRA (CMSSM) model

★ allowed parameter space: mSUGRA model

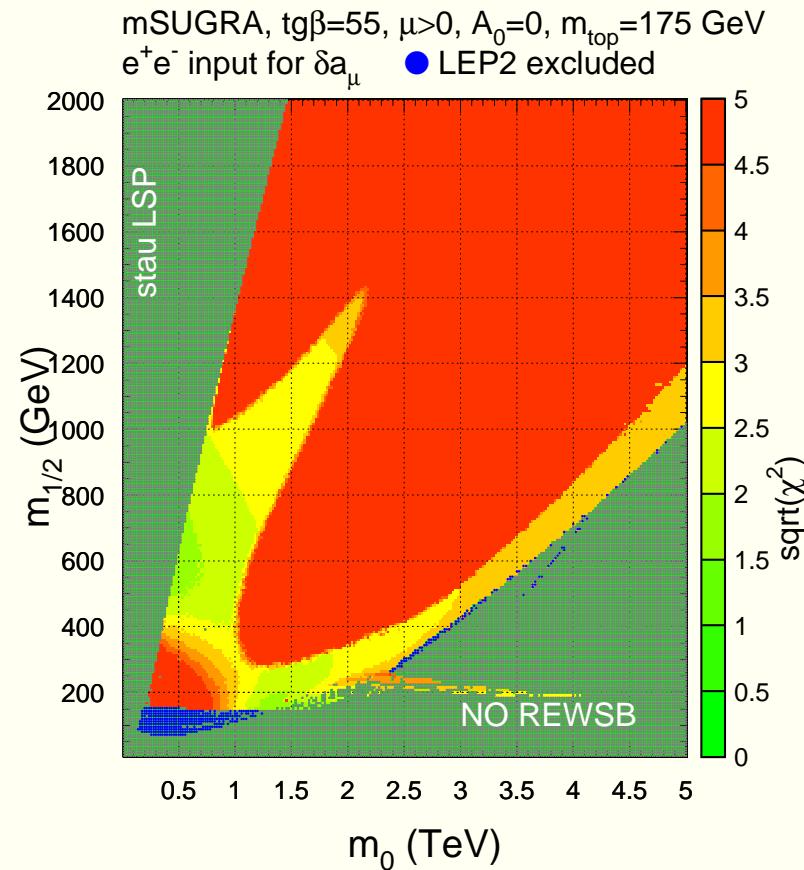
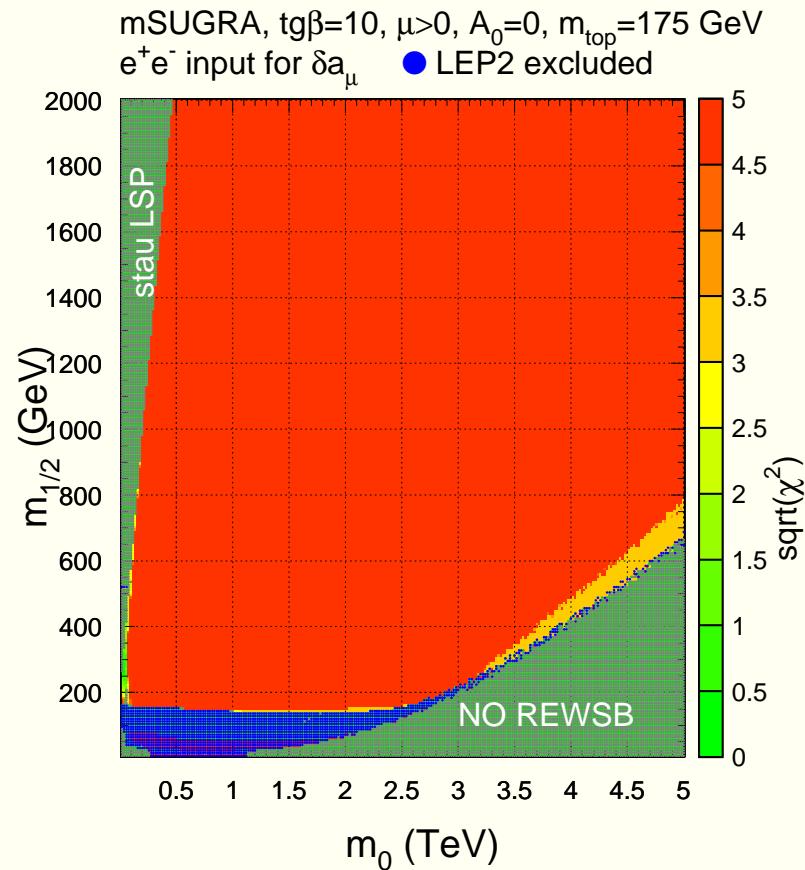
- $m_0, m_{1/2}, A_0, \tan\beta, sign(\mu)$



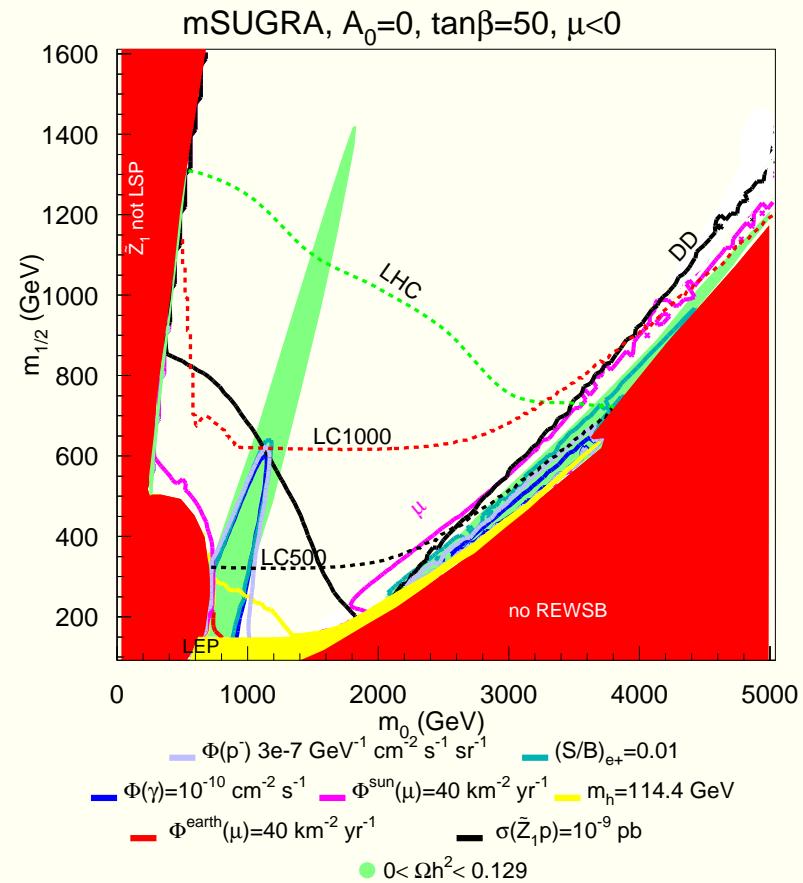
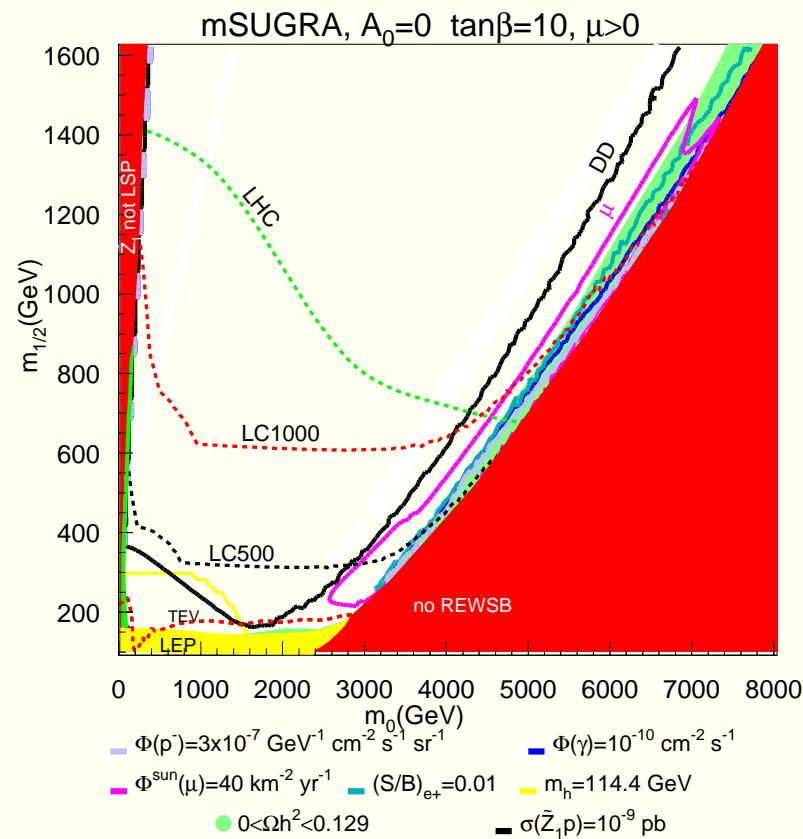
Main mSUGRA regions consistent with WMAP

- ★ most of parameter space excluded: $\Omega_{CDM} h^2$ too big!
- ★ Exceptions:
 - bulk region (low m_0 , low $m_{1/2}$)
 - stau co-annihilation region ($m_{\tilde{\tau}_1} \simeq m_{\tilde{Z}_1}$)
 - HB/FP region (large m_0 where $|\mu| \rightarrow small$)
 - A -funnel ($2m_{\tilde{Z}_1} \simeq m_A, m_H$)
 - h corridor ($2m_{\tilde{Z}_1} \simeq m_h$)
 - stop co-annihilation region (particular A_0 values $m_{\tilde{t}_1} \simeq m_{\tilde{Z}_1}$)

χ^2 from $\Omega_{\tilde{Z}_1} h^2$, $(g - 2)_\mu$, $BF(b \rightarrow s\gamma)$



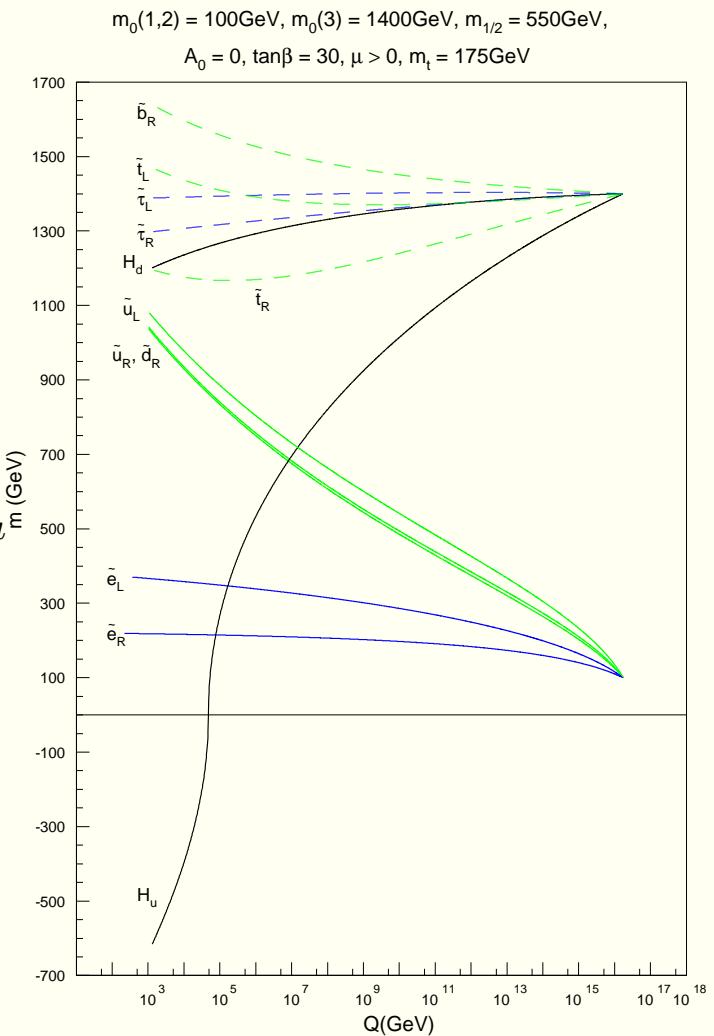
Direct, indirect, collider detection of neutralino DM



HB, Belyaev, Krupovnickas, O'Farrill

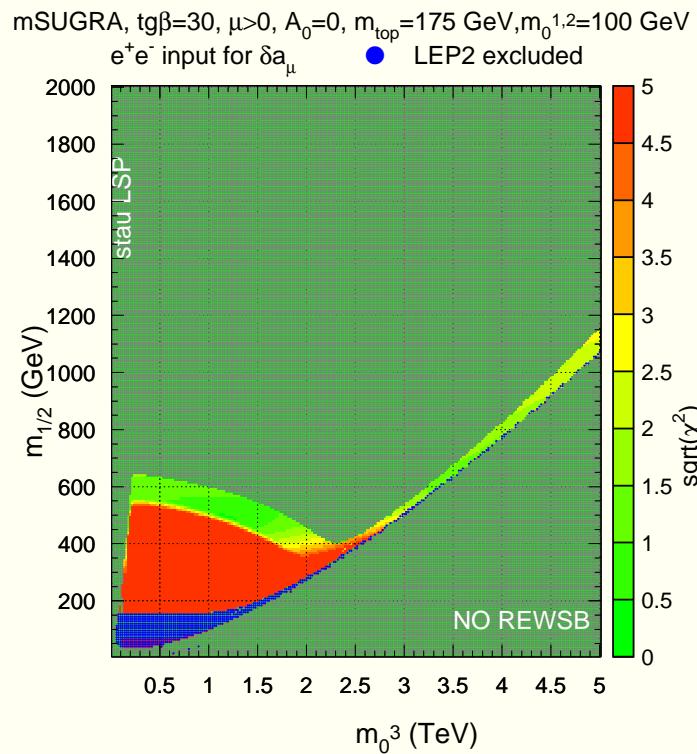
Case 2: non-universal generations

- Normal scalar mass hierarchy (NMH):
- $BF(b \rightarrow s\gamma)$ prefers heavy 3rd gen. squarks
- $(g - 2)_\mu$ prefers light 2nd gen. sleptons
- $m_0(1) \simeq m_0(2) \ll m_0(3)$
 - (preserve FCNC bounds)
- motivation: reconcile $BF(b \rightarrow s\gamma)$ with $(g - 2)_\mu$
 - HB, Belyaev, Krupovnickas, Mustafayev
 - JHEP 0406, 044 (2004)



Normal scalar mass hierarchy: parameter space

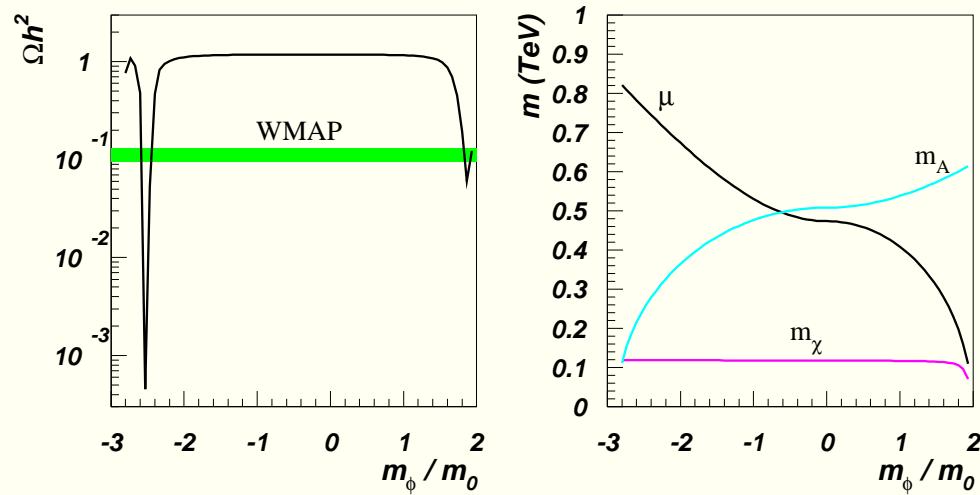
- $m_0(1) \simeq m_0(2) \ll m_0(3)$
- LHC: light sleptons, enhanced leptonic cascade decays
- ILC: first two gen. sleptons likely accessible; squarks/staus heavy



Case 3: NUHM1 (non-universal Higgs mass: 1 param.)

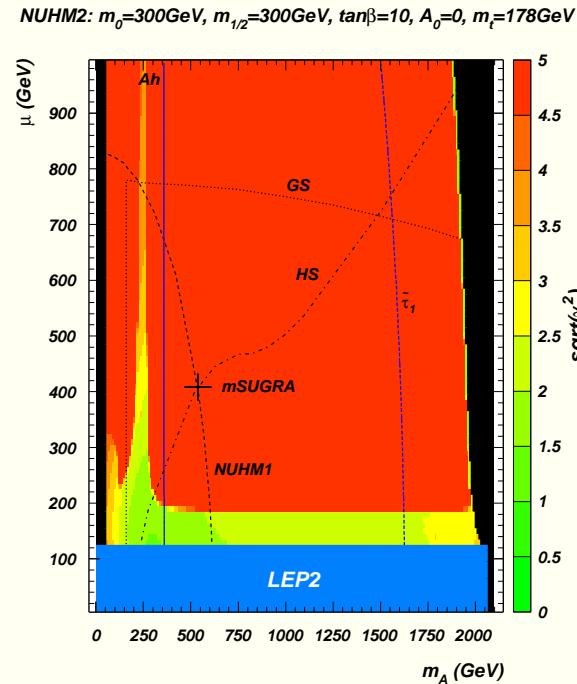
- $m_{H_u}^2 = m_{H_d}^2 \equiv m_\phi^2 \neq m_0$: Drees; HB, Belyaev, Mustafayev, Profumo, Tata
- motivation: $SO(10)$ SUSYGUTs where $\hat{H}_{u,d} \in \phi(10)$ while matter $\in \psi(16)$
- $m_\phi^2 \gg m_0 \Rightarrow$ higgsino DM for any $m_0, m_{1/2}$
- $m_\phi^2 < 0 \Rightarrow$ can have A -funnel for any $\tan\beta$

$m_0=300\text{GeV}, m_{1/2}=300\text{GeV}, \tan\beta=10, A_0=0, \mu>0, m_t=178\text{GeV}$



Case 4: NUHM2 (2-parameter case)

- $m_{H_u}^2 \neq m_{H_d}^2 \neq m_0$: HB, Belyaev, Mustafayev, Profumo, Tata
- motivation: $SU(5)$ SUSYGUTs where $\hat{H}_u \in \phi(5)$, $\hat{H}_d \in \phi(\bar{5})$
- can re-parametrize $m_{H_u}^2$, $m_{H_d}^2 \leftrightarrow \mu$, m_A (Ellis, Olive, Santoso)
- large S term in RGEs \Rightarrow light \tilde{u}_R , \tilde{c}_R squarks, $m_{\tilde{e}_L} < m_{\tilde{e}_R}$



Non-universal gaugino masses: case 5-7

★ Motivation:

- SUGRA models where GKF transforms non-trivially (Snowmass '96)
- Heterotic superstring models with orbifold compactification: SUSY breaking dominated by the moduli field
- KKLT model of type IIB string compactification with fluxes
- Extra-dimensional SUSY GUT models where SUSY breaking is communicated from the SUSY breaking brane to the visible brane via gaugino mediation (e.g. Dermisek-Mafi model)
- ...

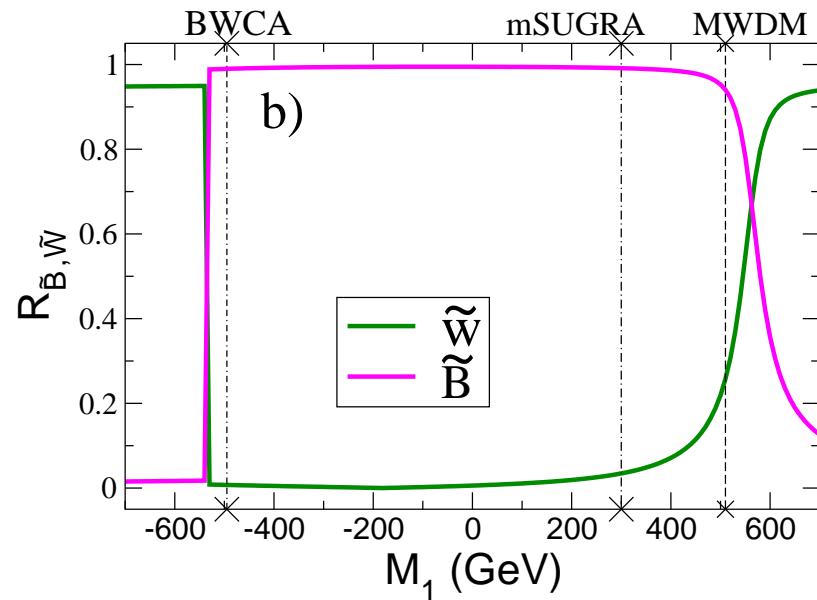
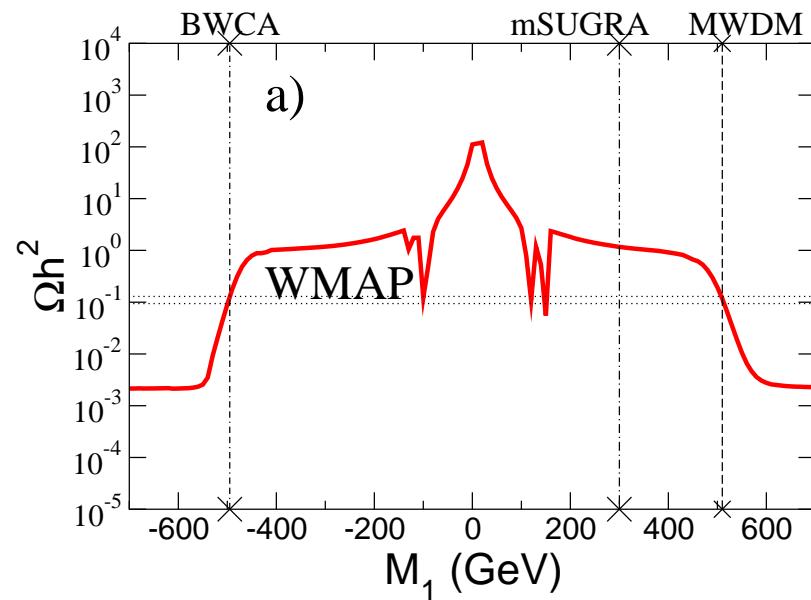
★ Here we adopt a phenomenological approach:

- independent M_1 , M_2 , M_3 , but require consistency with WMAP
 - * MWDM: HB, Mustafayev, Park, Profumo, JHEP0507, 046 (2005)
 - * BWCA DM: HB, Krupovnickas, Mustafayev, Park, Profumo, Tata, JHEP0512 (2005) 011.

- * LM3DM: HB, Mustafayev, Park, Profumo, Tata, JHEP0604 (2006) 041.
- Related work: Corsetti and Nath; Birkedal-Hansen and Nelson; Bertin, Nezri and Orloff; Bottino, Donato, Fornengo, Scopel; Belanger, Boudjema, Cottrant, Pukhov, Semenov; Mambrini, Munoz and Cerdeno; Auto, HB, Belyaev, Krupovnickas; Masiero, Profumo, Ullio

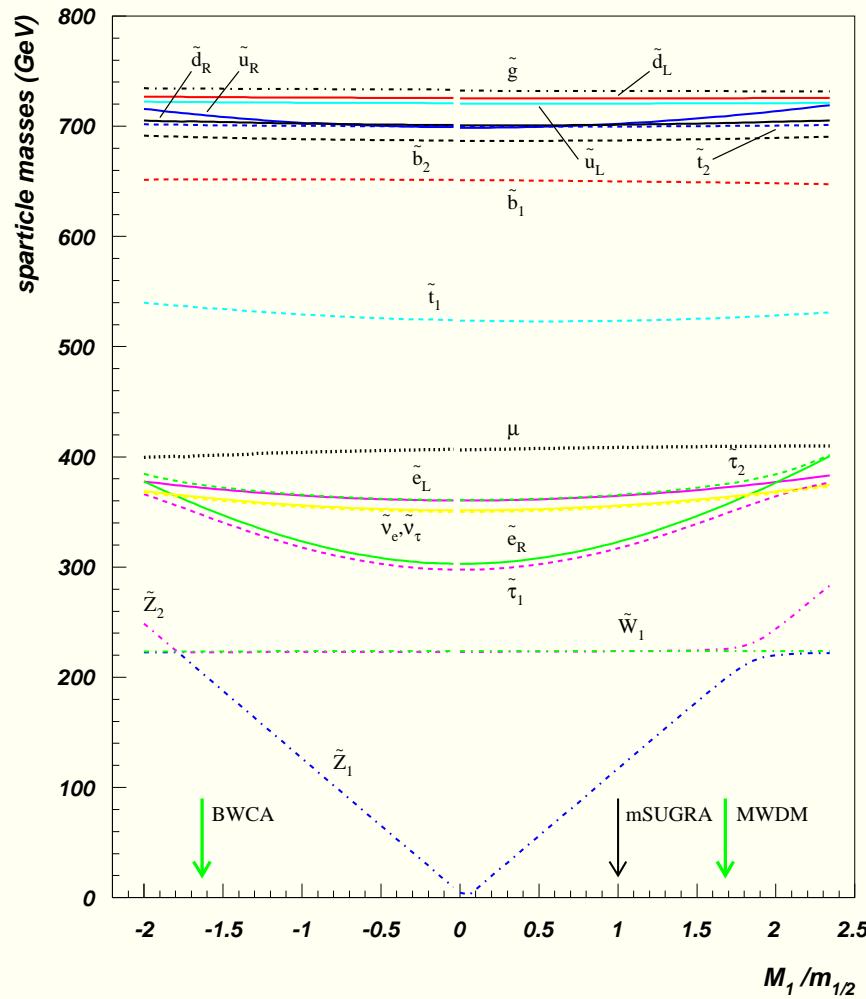
$\Omega_{\tilde{Z}_1} h^2$ vs. M_1

$m_0 = 300 \text{ GeV}, m_{1/2} = 300 \text{ GeV}, \tan\beta = 10, A_0 = 0, \mu > 0, m_t = 178 \text{ GeV}$



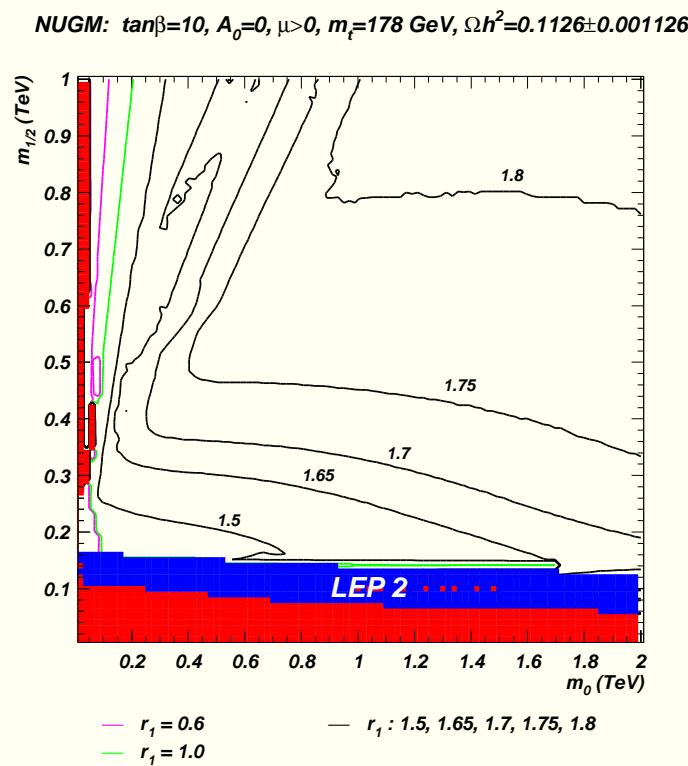
Sparticle mass spectra vs M_1

$m_0 = 300\text{GeV}$, $m_{1/2} = 300\text{GeV}$, $\tan \beta = 10$, $A_0 = 0$, $\mu > 0$, $m_t = 178\text{GeV}$



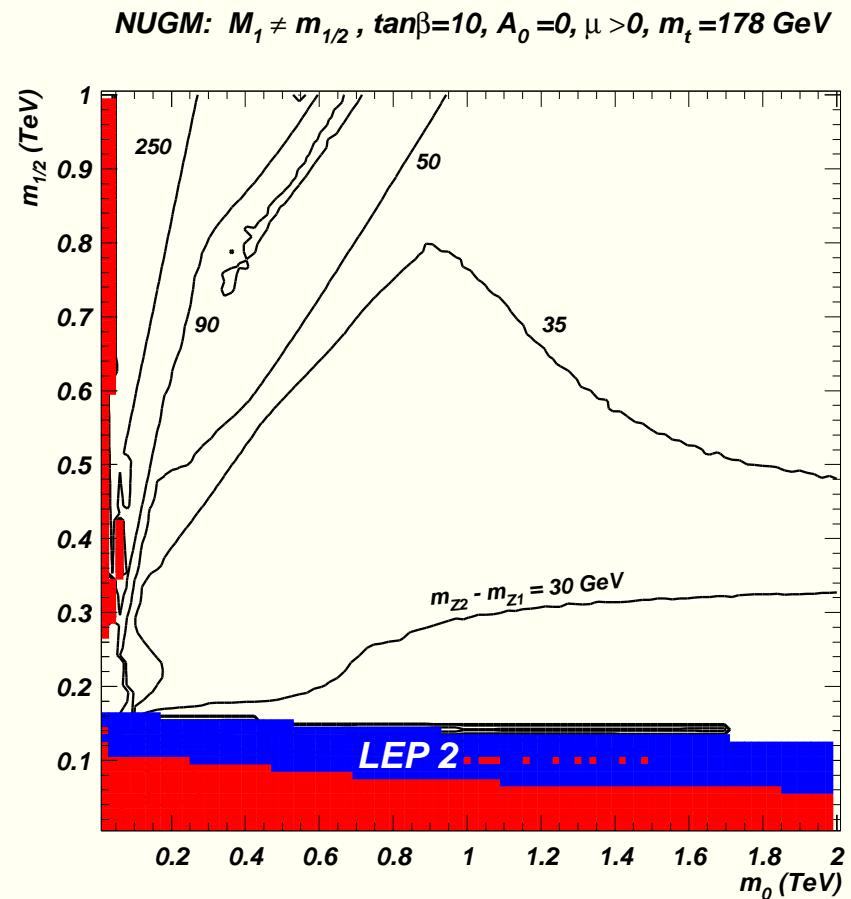
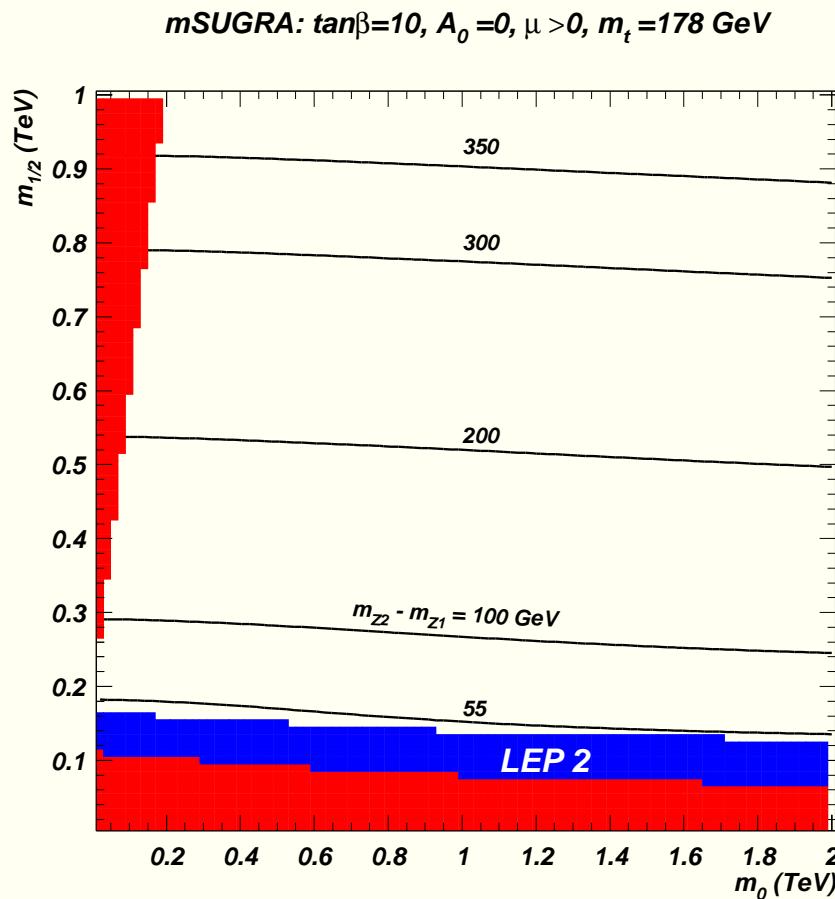
Case 5: MWDM (mixed wino DM)

- plot $r_1 \equiv M_1/M_2(M_{GUT})$ s.t. $\Omega_{CDM} h^2 \simeq 0.11$

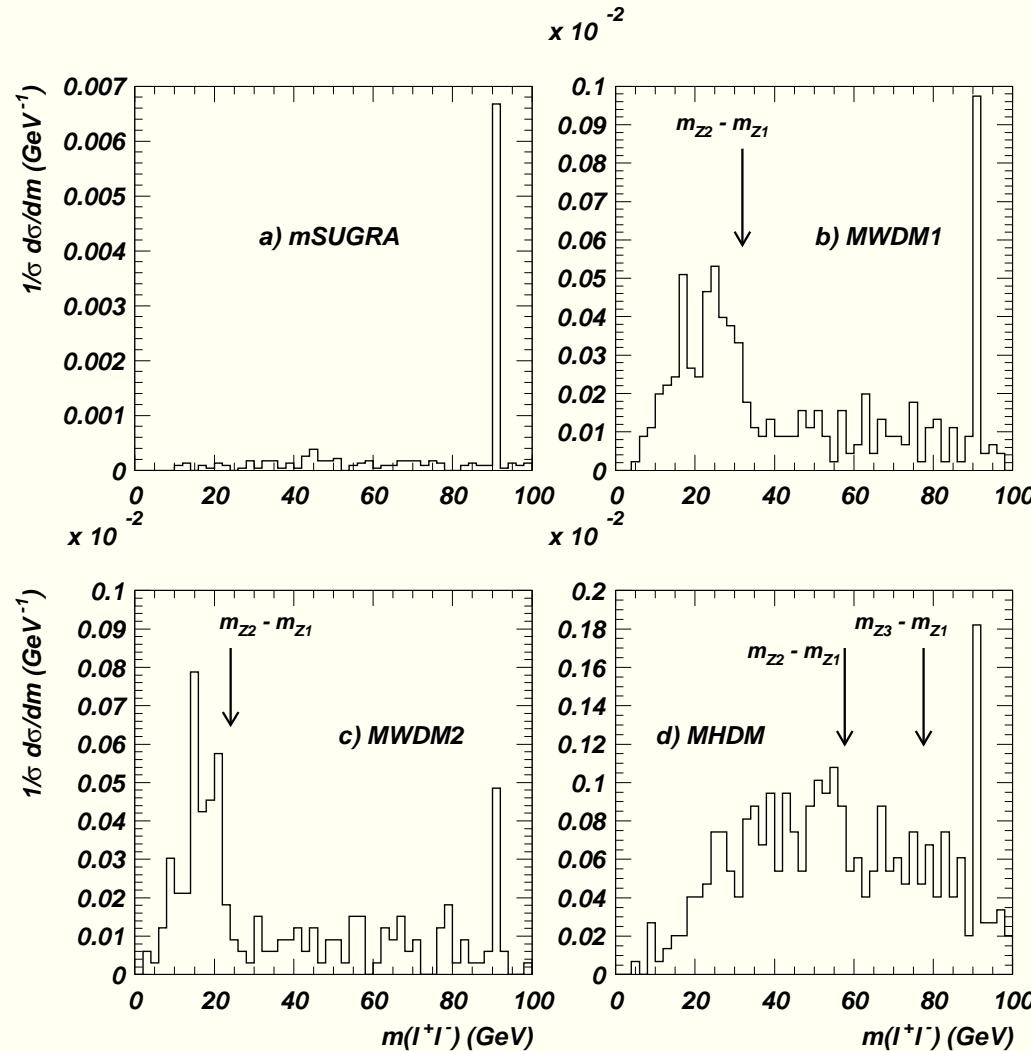


MWDM: small $\tilde{Z}_2 - \tilde{Z}_1$ mass gap

- mSUGRA: $m_{\tilde{Z}_2} - m_{\tilde{Z}_1} \sim m_{\tilde{g}}/7$
- MWDM: $m_{\tilde{Z}_2} - m_{\tilde{Z}_1} \sim 20 - 60$ GeV: two body \tilde{Z}_2 decays closed!

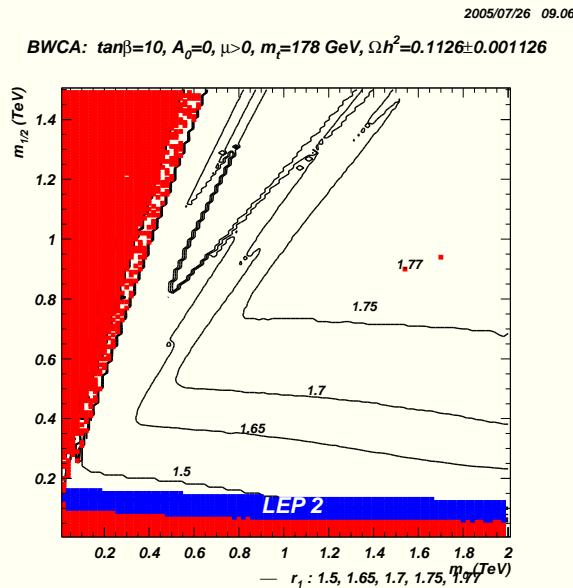


$m(\ell^+\ell^-)$: mass gap observable at LHC for MWDM

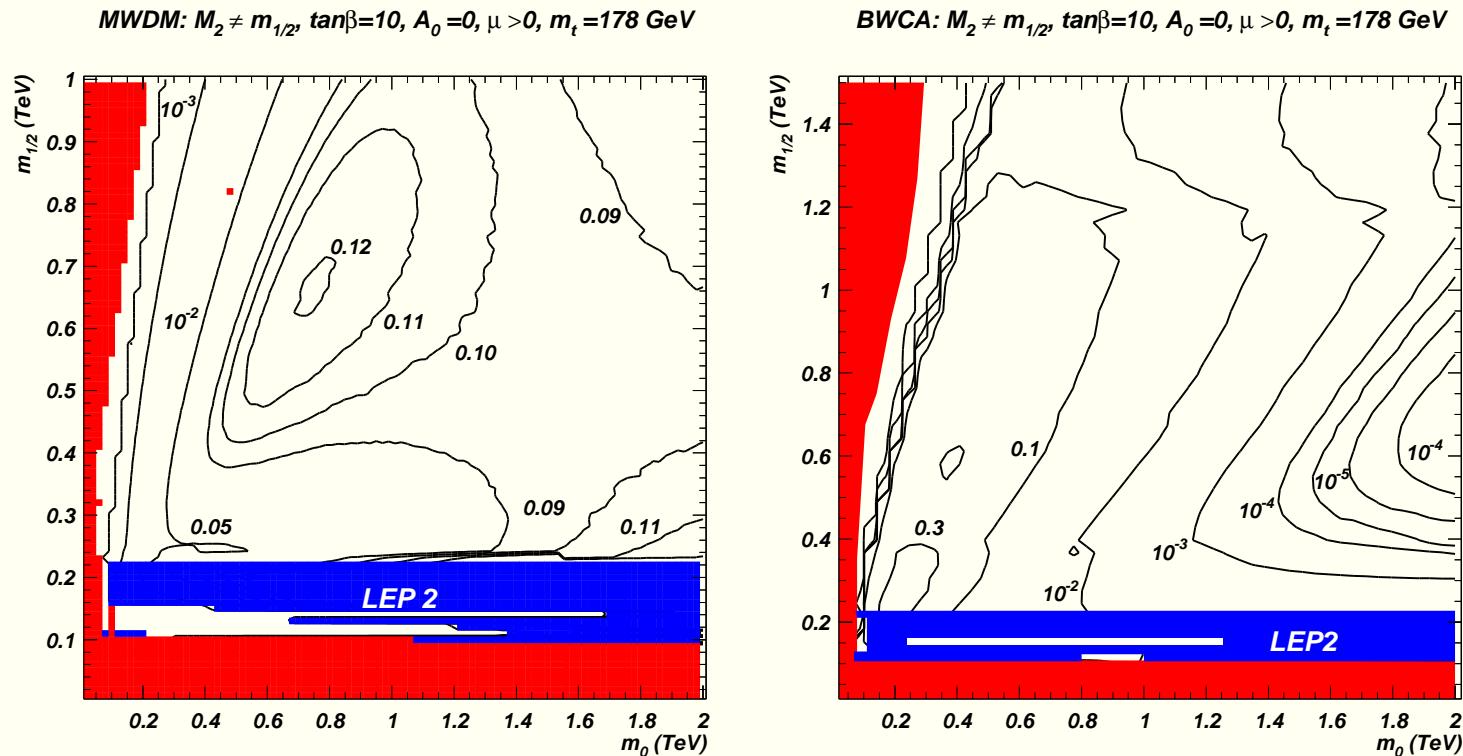


Case 6: Bino-wino co-annihilation (BWCA)

- If $M_1/M_2 < 0$, then no mixing between bino-wino
- Can only reduce relic density via bino-wino co-annihilation ($m_{\widetilde{Z}_1} \sim m_{\widetilde{W}_1} \sim m_{\widetilde{Z}_2}$) when $M_1 \simeq -M_2$ at $Q = M_{weak}$
- plot $r_1 = -M_1/M_2(M_{GUT})$

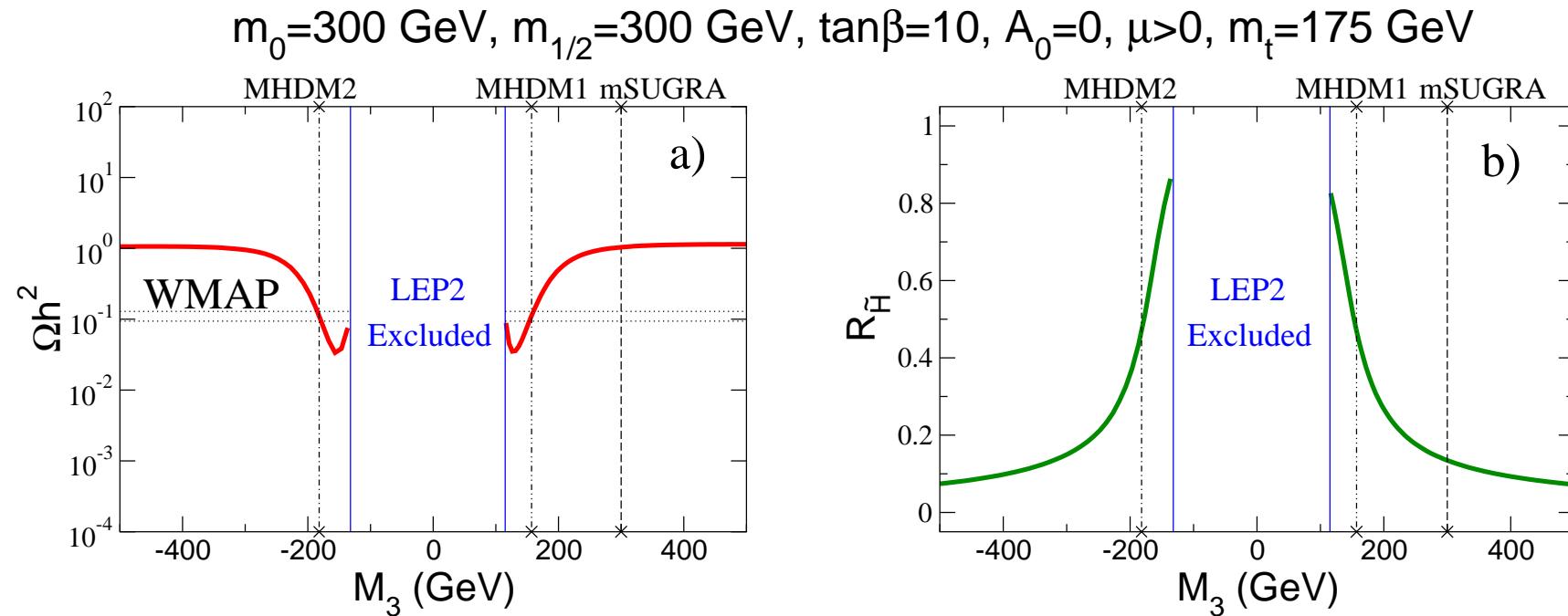


In BWCA at $m_0 \lesssim 500$ GeV, $BF(\tilde{Z}_2 \rightarrow \tilde{Z}_1 \gamma)$ enhanced!



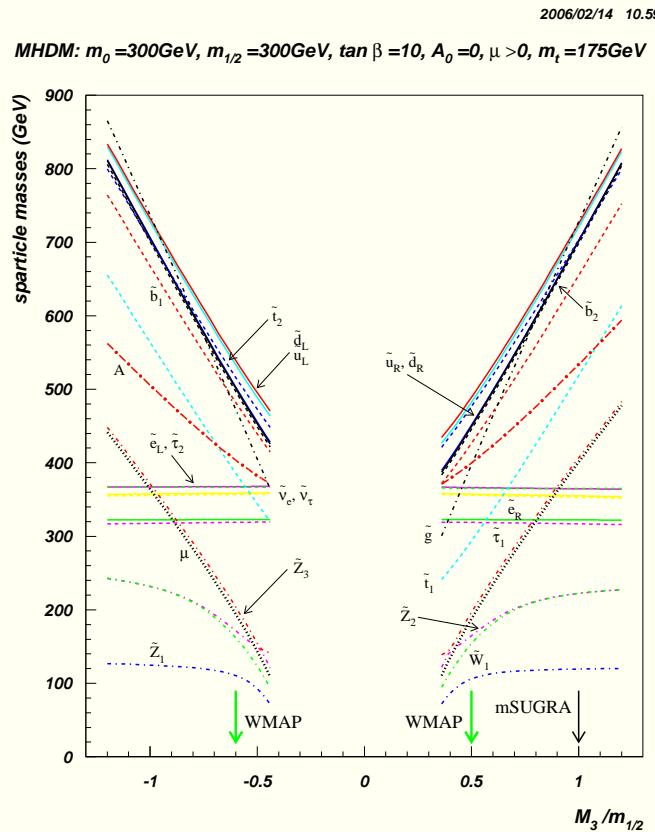
Haber+Wyler; Ambrosanio+Mele; Baer+Krupovnickas: JHEP 0209, 038 (2002)

Case 7: LM3DM (mixed higgsino DM from a low M_3)



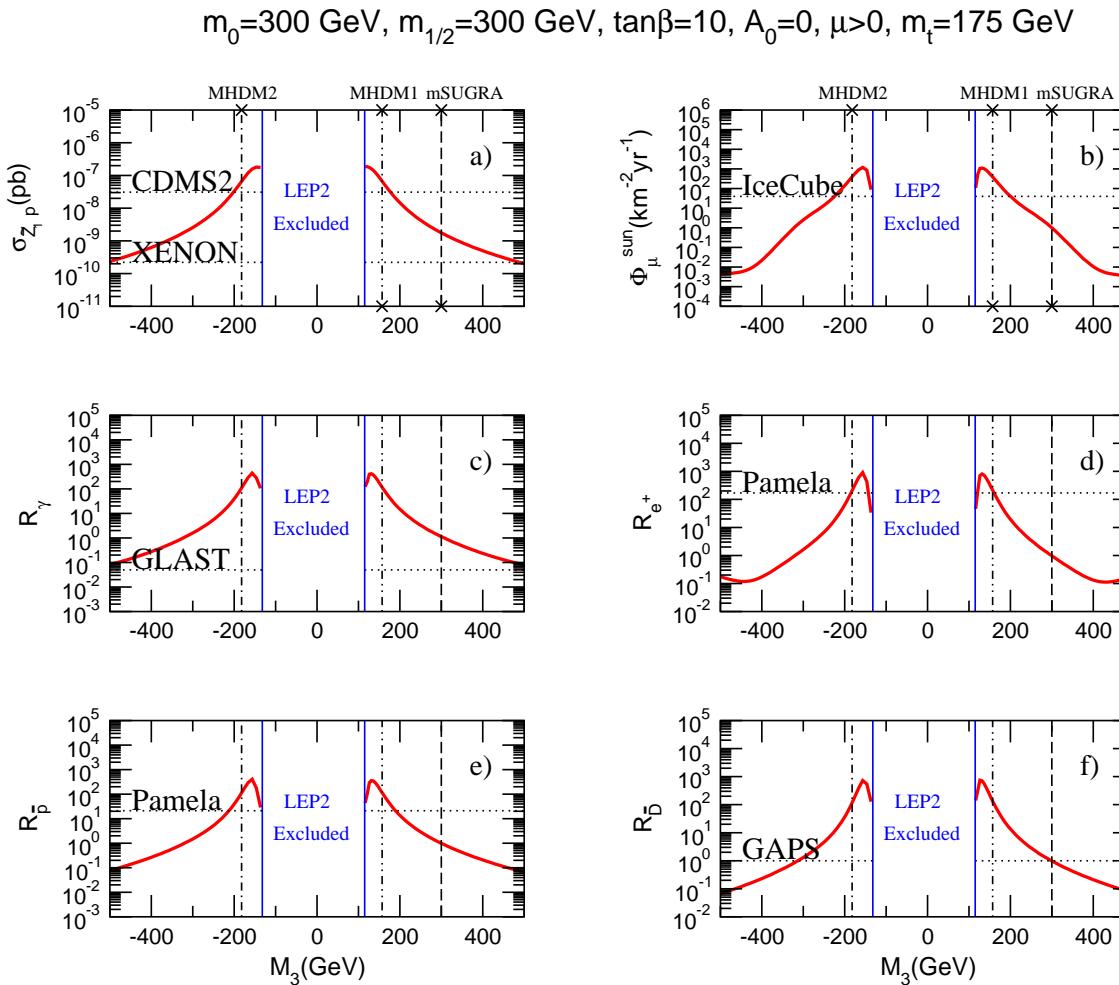
- low $M_3 \Rightarrow$ low $m_{\tilde{g}}, m_{\tilde{q}}, \mu$
- called “compressed SUSY” in related scenario by S. P. Martin

Sparticle mass spectra for LM3DM

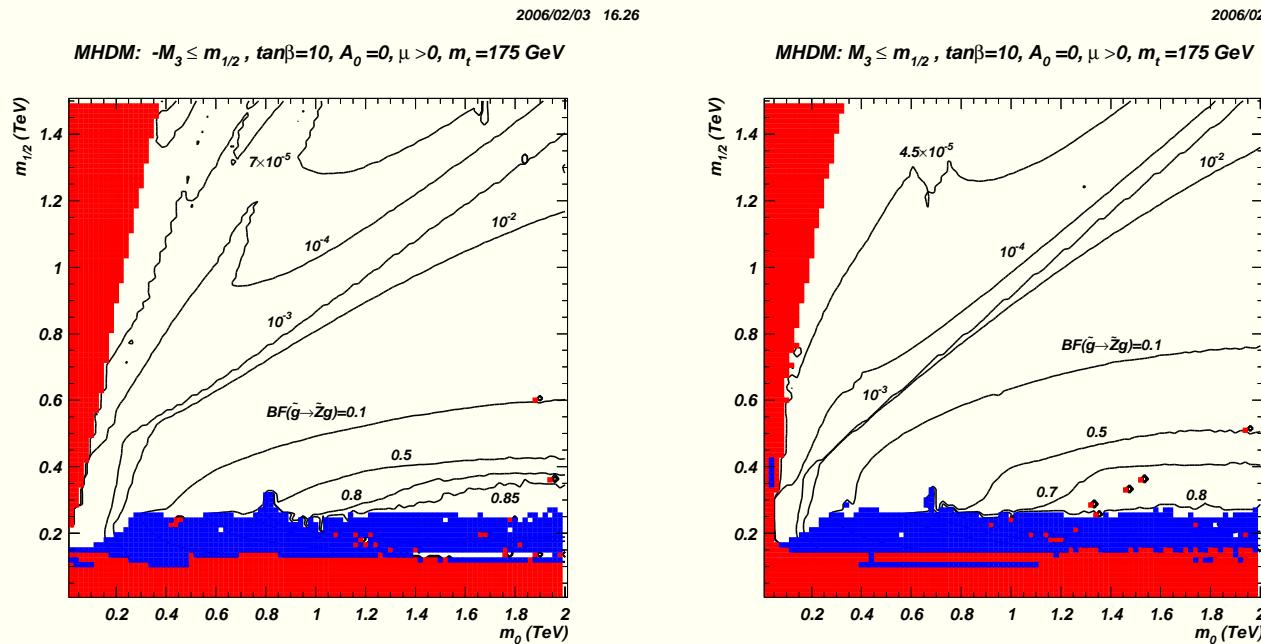


- low $m_{\tilde{g}}$, $m_{\tilde{q}}$, $\mu \Rightarrow$ huge DM detection rates!

Direct/indrct DM rates greatly enhanced for LM3DM



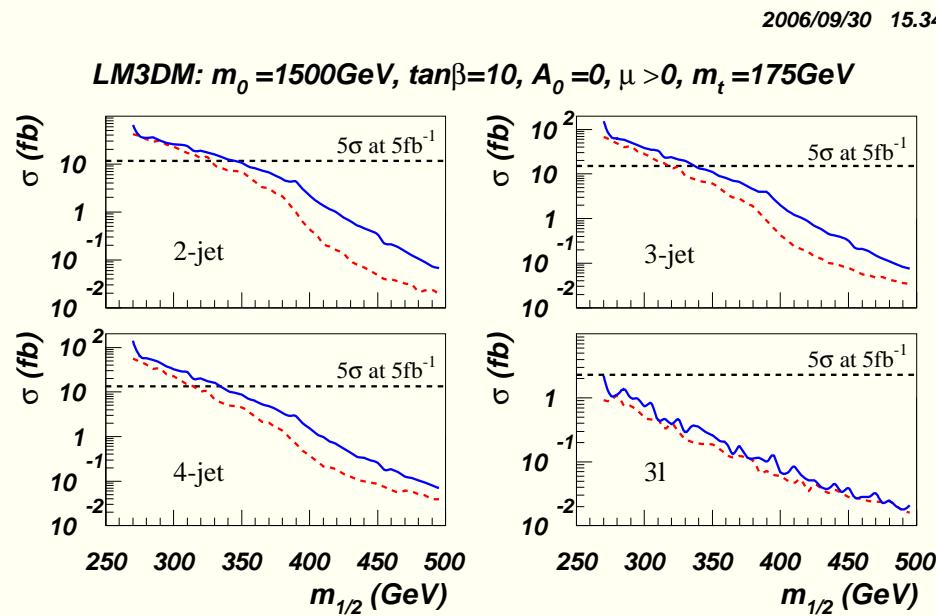
In LM3DM, $BF(\tilde{g} \rightarrow \tilde{Z}_i)$ loop decay enhanced!



Baer, Tata, Woodside: PRD42 (1990) 1568.

In LM3DM, ratio $m_{\tilde{g}} : m_{\widetilde{W}_1} : m_{\widetilde{Z}_1} \sim 2.5 : 1.5 : 1$

- Can search for $p\bar{p} \rightarrow \tilde{g}\tilde{g} \rightarrow jets + E_T$ at Tevatron;
- Search is *not* pre-empted by LEP2 bounds on $m_{\widetilde{W}_1}$
- Can see $m_{\tilde{g}}$ from 200 – 340 GeV: HB, Mustafayev, Tata PRD75,035004 (2007)



Case 8: Mixed modulus-AMSB (mirage unification)

- ★ KKLT model: type IIB superstring compactification with fluxes
 - stabilize moduli/dilaton via fluxes and e.g. gaugino condensation on $D7$ brane
 - introduce anti- $D3$ brane (uplifting potential; de Sitter universe with $\Lambda > 0$)
 - small SUSY breaking due to $\overline{D3}$ brane
 - mass hierarchy: $m_{moduli} \gg m_{3/2} \gg m_{SUSY}$
- ★ MSSM soft terms calculated by Choi, Falkowski, Nilles, Olechowski, Pokorski
- ★ phenomenology: Choi, Jeong, Okumura, Falkowski, Lebedev, Mambrini, Kitano, Nomura
- ★ see also: HB, E. Park, X. Tata, T. Wang, JHEP0608, 041 (2006); PLB641, 447 (2006); hep-ph/0703024.

Parameter space of MM-AMSB (mirage unification) model

- MSSM sparticle mass scale $\sim \frac{m_{3/2}}{16\pi^2} \equiv M_s$
- Ratio of modulus-mediated and anomaly-mediated contributions set by a phenomenological parameter α
- Modulus-mediated contributions depend on location of fields in extra dimensions. These contributions depend on “modular weights” of the fields, determined by where these fields are located.
 - modular weights $n_i = 0$ (1) ($(\frac{1}{2})$) for D7 (D3) ((intersection))
 - Gauge kinetic function indices $l_a = 1$ (0) on $D7$ ($D3$) branes.

Model completely specified by

$$m_{3/2}, \alpha, \tan \beta, \text{sign}(\mu), n_i, l_a$$

- Radiative EWSB determines μ^2 as usual; model into Isajet 7.75

Soft SUSY Breaking Terms

The soft terms renormalized at $Q \sim M_{\text{GUT}}$ are given by,

$$M_a = M_s (\ell_a \alpha + b_a g_a^2),$$

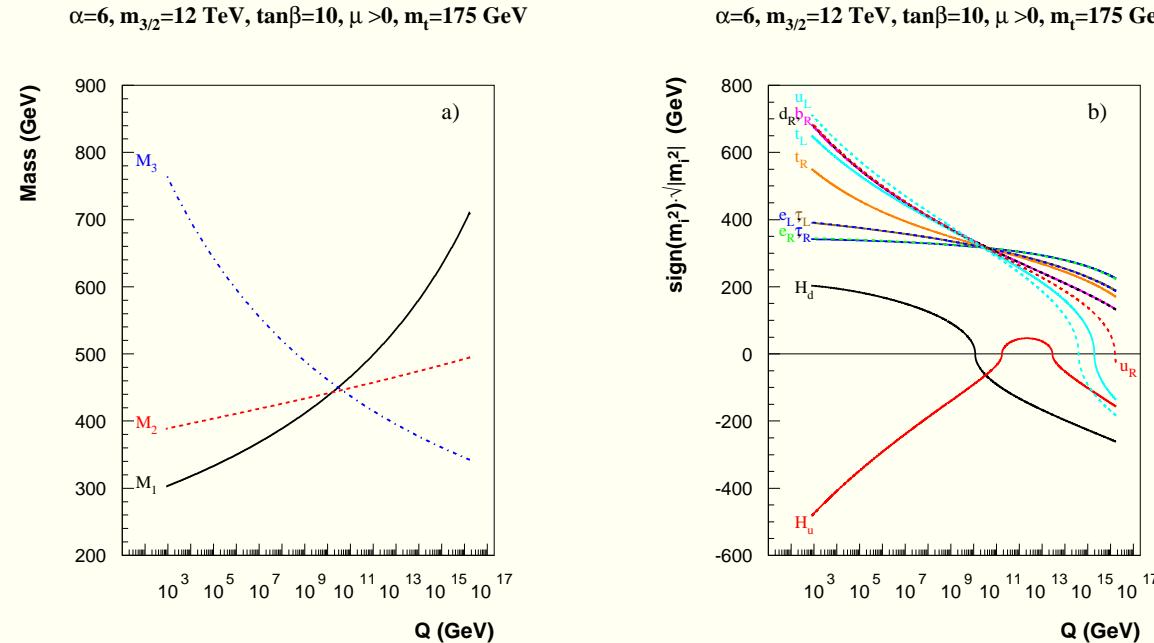
$$A_{ijk} = M_s (-(3 - n_i - n_j - n_k) \alpha + \gamma_i + \gamma_j + \gamma_k),$$

$$m_i^2 = M_s^2 ((1 - n_i) \alpha^2 + 4 \alpha \xi_i - \dot{\gamma}_i),$$

with

$$\xi_i = \sum_{j,k} (3 - n_i - n_j - n_k) \frac{y_{ijk}^2}{4} - \sum_a l_a g_a^2 C_2^a(f_i), \text{ and } \dot{\gamma}_i = 8\pi^2 \frac{\partial \gamma_i}{\partial \log \mu}$$

Can measure modular weights in MM-AMSB model

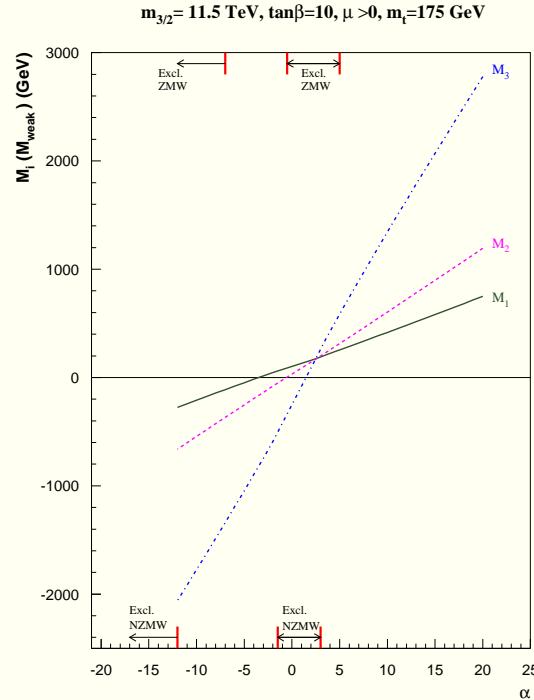


At $Q = \mu_{\text{mir.}}$, ratio of scalar to gaugino masses is given by

$$\frac{m_i}{M_a} \Big|_{\mu_{\text{mir}}} = \frac{\sqrt{1 - n_i}}{l_a}.$$

For $l_a = 1$, this measures the matter modular weight!

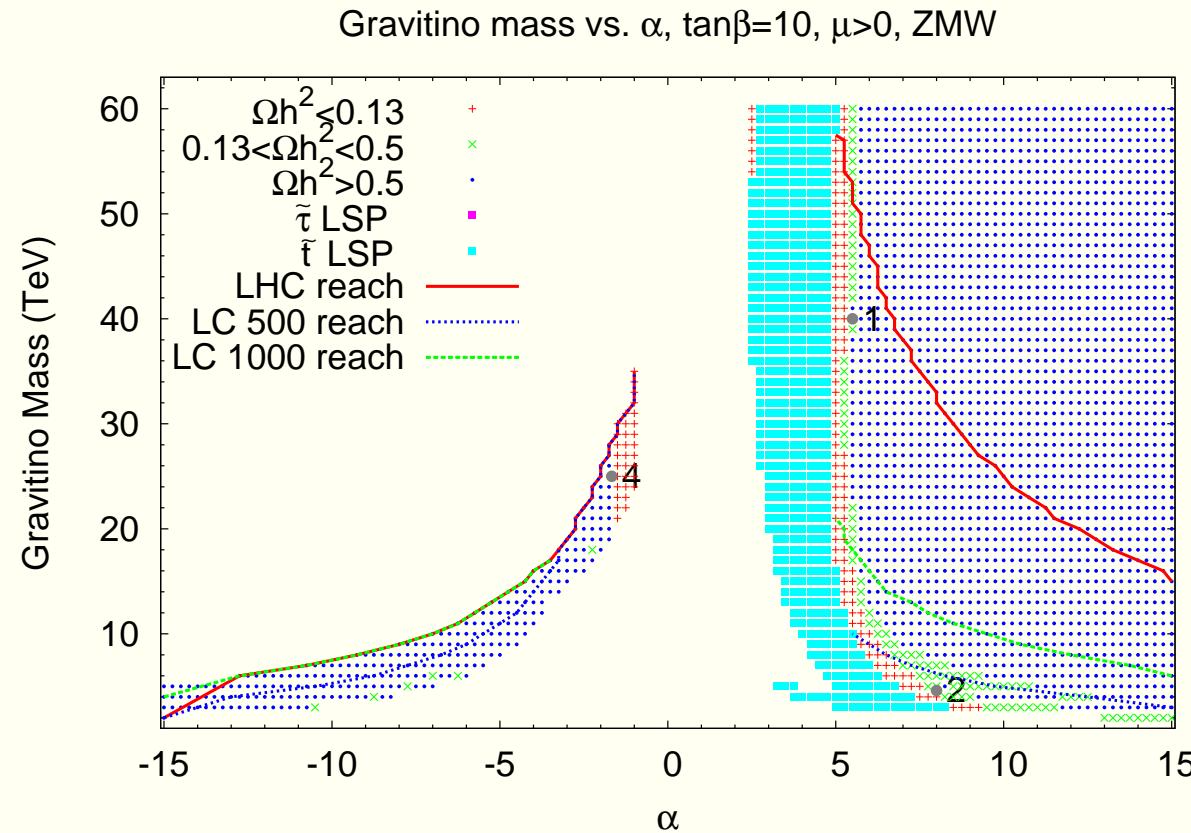
Gaugino masses at weak scale in MM-AMSB:



Low mirage unification scale

If $M_1(\text{weak}) = \pm M_2(\text{weak})$, potential for agreement with relic density via MWDM or BWCA!

α vs. $m_{3/2}$ space for $n_m = n_H = 0$:

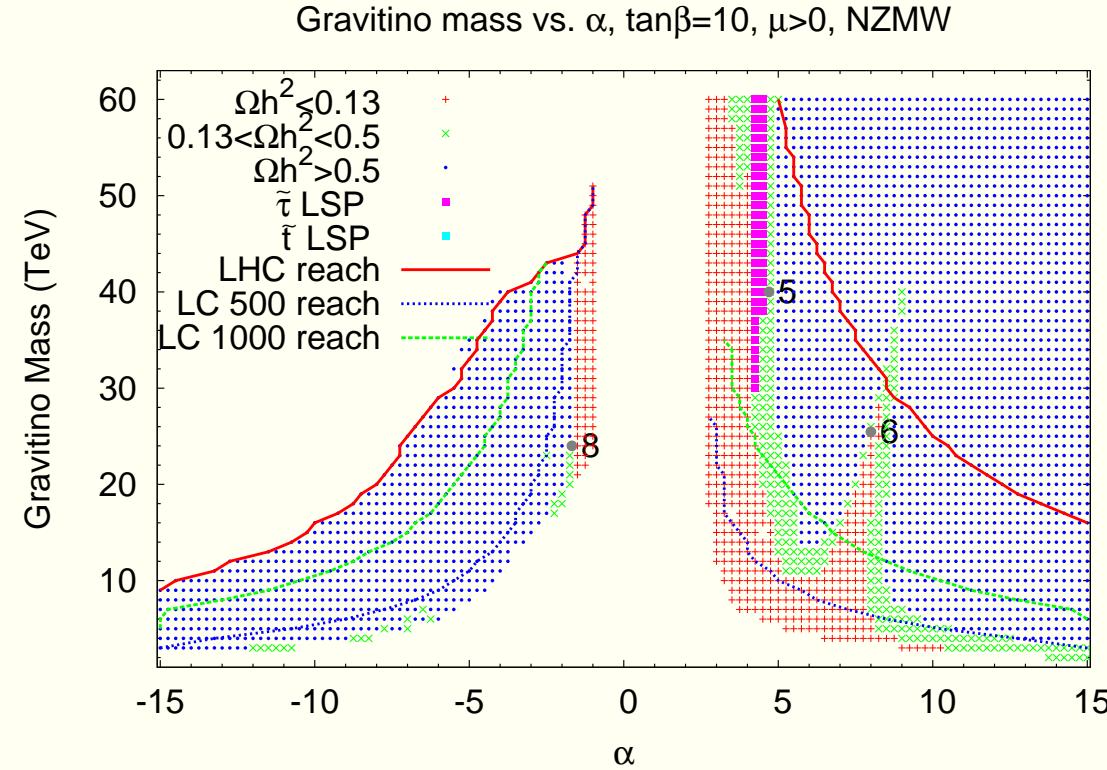


Stop coannihilation region.

Mixed higgsino region at low positive alpha.

BWCA for $\alpha < 0$. No MWDM region.

α vs. $m_{3/2}$ space for $n_m = \frac{1}{2}$, $n_H = 1$:



Stau coannihilation, Higgs funnel, MWDM and BWCA regions clearly seen.
Also, mixed bino-wino-higgsino region (via low $|M_3|$).
Bulk region at low $m_{3/2}$.

Conclusions: SUSY dark matter models

- ★ We use the measured relic density of CDM as a guide to SUSY phenomenology in the MSSM
 - mSUGRA models: allowed regions
 - NMH
 - NUHM1
 - NUHM2
 - MWDM
 - BWCA DM
 - LM3DM
 - mixed moduli-AMSB (KKLT, mirage unification)
- ★ data coming soon from LHC will be final arbiter!